Qualifying a Cleaning System for Space Flight Printed Wiring Assemblies

by

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Abstract

During the last decade, the challenges of printed wiring assemblies (PWAs) have grown tremendously. Today printed wiring boards have grown more complex to meet the continuing challenges posed by the increasing uses of microdevices such as fine pitch packages and array devices such as ball grid arrays, microball grid arrays, and flip chips. Multilayer boards with a large layer count and narrow trace widths and spaces are commonplace. The ball grid arrays, microball grid arrays, and other small devices generally have a large number of I/Os, small standoffs, and small pitches. The small standoff and small pitch, coupled with the complex circuitry needed to route such components, makes cleaning an ever more critical operation. High reliability PWBAs cannot tolerate contaminants since their presence can potentially degrade the board, thus compromising the intended mission. Cleaning for high performance PWAs is normally performed as a minimum at the following stages:

(1) At the bare PWB stage prior to the application of solder mask;
(2) Immediately after the PWB + components are soldered to form the PWA;
(3) Immediately prior to the application of conformal coating.

If the PWAs are properly stored, the second and third operations are sometimes combined. In addition to cleaning, some sort of cleanliness verification method is employed to ascertain that a certain level of cleanliness has been achieved. The most common cleanliness verification method has been ionic contamination testing using an industry-recognized device such as an Ionograph® or Omega-Meter®. Today, however, determining the amount of residual rosin (assuming that a rosin-based flux or paste was used) is often done. Another useful technique is to remove some of the components and examine for flux residues both visually and by use of a microscope.

In addition to all this, the last decade has also seen the dramatic decrease and continuing disuse of ozone-depleting solvents. The common chlorofluorocarbon solvents, such as Freon® TMS, have been discontinued, and many PWA assemblers have switched to more environmentally friendly cleaning agents, such as a wide variety of semi-aqueous and aqueous-based materials. To enhance the performance of such materials, the proper equipment selection plays a critical role.

This paper addresses a centrifugal cleaning system used in conjunction with a water-based cleaning medium to achieve optimally low levels of contaminants on PWAs. Ionograph data, ion chromatography profiling, residual rosin determination, and outgassing data are presented demonstrating the effectiveness of the centrifugal cleaning system and the cleaning agent for space flight printed wiring assemblies.

Background

Ten years ago the Electronic Packaging and Fabrication section at JPL established a dedicated facility for producing very low volume but high performance surface mount technology (SMT) assemblies known as the SMT Laboratory. This laboratory has successfully assembled SMT PWAs for such important JPL programs as these:

- Cassini;
- ChuG Microgyro;
- Caltech - ACE;
- MISER;
- SEAWINDS,
- Pathfinder, etc.

and many others. Since the assemblies produced in this laboratory always fall in the high performance, high reliability category, cleaning is mandatory, not optional. With the demise of the ozone-depleting solvents that were the mainstay of the electronics industry for twenty years, it was necessary to turn to alternative chemistries and cleaning systems to ensure cleanliness and high reliability of the SMAs.

In addition, the following JPL process information is pertinent to the discussion:

- Rosin-based fluxes and pastes are used to produce all electronic hardware. Using the terminology of Mil-F-14256, the classification of these products is RMA.
- The solder paste is applied using a semi-automated screen printer ensuring that the paste is deposited in a uniform and consistent manner. Only stainless-steel stencils are used in conjunction with a stainless-steel squeegee. All boards are visually inspected for proper paste deposition after the stencil operation.
- A laser-based solder paste height and width measurement system is used with a resolution of 0.0001". This system provides real time information on the uniformity of solder paste deposition. All boards are subjected to this measurement prior to the reflow operation.
- A batch reflow operation is used to create the solder joints of the SMT PWAs. The SMT PWAs are thermally profiled using a MOLE® to eliminate thermal shock during preheat and reflow. This operation consists of a vapor phase reflow machine using a constant boiling perfluorocarbon material (3M Perfluorocompound® FC-5312) (b.p. 216°C) is used to solder the SMT PWAs. The SMT PWAs are preheated to remove paste volatiles and to initiate the activation stage of the paste. The reflow liquid, since it boils at a constant temperature, minimizes the possibility of overheating the SMT PWAs during reflow and ensures that the vapor blanket performs a uniform and consistent soldering operation.

Necessity of Cleaning for High Performance PWAs

During both the fabrication process of the bare PWB and the assembly process whereby components are metallurgically joined to the PWB by using a suitable solder paste, a number of contaminants are potentially introduced on the PWB surface. These contaminants can be classified into three broad categories:

(1) Particulates;

(2) Ionic residues;
(3) Non-ionic residues, chiefly organic in nature.

For a more detailed summary of the individual contaminant types found in each category, see Bonner (1991).

To ensure the reliability of a PWA, cleaning is mandatory to remove these contaminants after the soldering operation and also directly prior to the application of a conformal coating. Failure to remove them to an acceptable level can result in premature failure of the PWA or failure to perform as intended in the specified service environment. The testing to qualify a new cleaning system is detailed below in this paper.

Previous Cleaning System

The initial cleaning system chosed for the SMT Laboratory is a two-stage batch semi-aqueous (SA) cleaning system. To minimize oxidation of the PWA, the entire system is purged with dry nitrogen gas (N_2). The first stage consists in placing the PWAs vertically in a suitable conventional rack followed by cleaning using a terpene-based SA material and D.I. water. The PWAs are then transferred to the second machine and rinsed using a suitable saponifier, isopropyl alcohol (IPA), and D.I. water. This machine incorporates an automatic ionic monitoring and control system. The resistivity is never allowed to drop below 2 MΩ-cm. If this happens, the PWAs are recleaned until this level was achieved.

Although this system worked satisfactorily for a number of years, the decision was reached recently to replace it. Part of the reason was the increasing complexity of the SMT PWAs. It was deemed necessary to find a piece of cleaning equipment to ensure that the cleaning chemistry would successfully penetrate under the small standoffs and tight spacings found under the newer components now being increasing employed, such as fine pitch components and area array devices such as ball grid arrays (BGAs). Another factor was the initial equipment manufacturer sold off this portion of the business and no longer supported the equipment. It proved increasingly more difficult to maintain the equipment in good working condition. In addition, the use of IPA has come under increasing scrutiny by the South Coast Air Quality Management District (SCAQMD). Because IPA is a VOC, its emission into the atmosphere is under tight control. So last year the decision was made to investigate a new cleaning system and a chemistry that would support JPL's need for clean PWAs while avoiding the increasing problems with the batch SA cleaning system.

Criteria for Choosing a New Cleaning System

There are several distinct criteria used in choosing a new cleaning system. The key criteria are:

- Safety and ease of handling;
- Performance;
- Cost.

Since JPL's needs are very low throughput, a batch cleaning system was acceptable. After various preliminary trials were conducted, a centrifugal cleaning system was chosed based both on performance and versatility. In addition, several new aqueous cleaning chemistries appeared that seemed very promising. One of these is based on a aqueous system containing long-chain linear alcohols. The material itself is easily biodegradable. It has 0 ODP, virtually no GWP, and is

classified as non-flammable. Although the concentrate is 91% by weight VOC, the material as used in the cleaning system is only 13.6% by weight VOC. JPL has obtained a permit from the South Coast Air Quality Management District (SCAQMD) to use the centrifugal cleaning system per Rule 1122. The total permissible VOC emission limit per day to obtain a permit is less than 1.0 lb. of VOC.

New Cleaning System

The new cleaning system consists of the following equipment and materials with a brief description of its operation.

Equipment

The following equipment is required:

- Centrifugal cleaning system;
- Vacuum oven;
- Refractometer.

Equipment Description

The equipment consists of an enclosed stainless steel cylindrical process chamber with a series of spray nozzles located vertically. A robotic arm containing a fixture holds PWA and moves in and out of the chamber vertically. During the cleaning cycle, the PWA is lowered into the process chamber until it is completely sealed from ambient. Figure 1 shows the centrifugal cleaning system.

Materials

The following materials are used in the centrifugal cleaning system:

- Aqueous system containing long-chain linear alcohols - 20% by volume;
- Corrosion inhibitor - 1% by volume;
- Defoamer - 0.1% by volume;
- Deionized (DI) water;
- High purity nitrogen gas (N_2).

NOTE: Hereafter the term "aqueous cleaning solution" shall refer to the entire aqueous system consisting of water, long-chain linear alcohols, corrosion inhibitor, and defoamer.

Principle of Operation

The centrifugal cleaning machine uses centrifugal energy to clean PWAs. Energy is produced when PWAs to be cleaned are rotated inside an enclosed process chamber filled with the aqueous cleaning solution (see Materials). This energy causes penetration of the solution under the components, including low profile components such as BGAs, solubilizing the contaminants. The contaminants are subsequently removed during the rinse operation.

Overall Process Description

The cleaning process consisted of four-stage operation. The first stage is a nitrogen purge of the process chamber. The second stage is a wash cycle with aqueous cleaning solution. The process chamber is filled with appropriate amount of aqueous cleaning solution. The PWA, while immersed in the solution, is rotated in the chamber for a predetermined duration. At the end of the

cycle, the solution is cycled back to the storage tank. During the third stage, the D.I. water rinse sprays are activated while the PWA is rotating in the chamber. During this cycle any leftover chemistry is removed, and final cleaning is achieved. In the fourth stage, filtered hot air is pumped in the chamber as the PWA rotates and dries. During these cycles, the PWA rotates alternately, clockwise and counter clockwise to achieve optimum cleaning and drying.

Testing of the New Cleaning System

In order to investigate the new cleaning system, a comparison was made between it and the initial cleaning system. The following objectivcs were pertinent to this investigation:

Objectives

There were two chief objectives. These were:

- Investigate the new centrifugal cleaner using the aqueous cleaning solution for flight PWAs;
- Establish the optimal cleaning cycle for the new equipment.

To be able to recommend the new centrifugal cleaner using the aqueous cleaning solution, the procedure used was to compare the cleaning data of older cleaning process using the SA solution with the centrifugal cleaner using the aqueous cleaning solution.

Testing Procedure

The testing procedure consisted of assemblying a test PWA that would prove challenging to clean. Several alternative cleaning runs using the new centrifugal cleaning equipment were made. The data so obtained was contrasted with (1) the test PWA used in the earlier SA cleaning system using the standard SA cleaning cycle, and (2) a test PWA not cleaned at all.

Test PWA

The test PWA was populated with BGAs, Chip Scale Package, QFPs (20-mil pitch and 25 mil pitch), a PLCC, a Flat Pack, an SOIC and several discrete chip capacitors and resistors. Both sides of the PWA were populated. See Figures 2 and 3. The test PWA was assembled using Sn 63 paste with RMA flux and soldered in a vapor phase reflow system operating at constant temperature of 216°C. See Figures 2 and 3.

Testing Parameters

The following testing parameters were employed:

- The basic equipment parameters of the centrifugal cleaning machine such as the temperature of the solution, the rotational speed of PWA and the drying temperature of the air were kept constant for all the tests.
- The only parameters that were varied were the cycle times:

    1. Wash cycle time;
    2. Rinse cycle time;
    3. Dry cycle time.

Cleanliness Determination Methods

The following methods were used to assess achieved cleanliness levels:

- Ionic contamination level data was obtained using an Ionograph® 500 ionic contamination tester. In addition, testing was performed using ion chromatography (IC) to profile the various ionic species.
- Total low volatility residue (LVR) consisted of an extraction with Freon® TF and isopropyl alcohol (IPA) followed by a gravimetric determination. The total LVR was considered to be equal to organic rosin residue since rosin residue predominates in flux residue.
- Residual chloride analysis (Cl^-) using ion chromatography (IC) was employed. For one run, residual fluoride analysis (F^-) and bromide analysis (Br^-) were also performed.
- Outgassing per ASTM E595, "Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment".

Either ionic contamination testing was performed using the Ionograph® 500 or total LVR was performed for a given sample, but not both. That is, the tests are mutually exclusive of each other. This is because in the process of conducting the ionic contamination test, the PWB is cleaned, thus rendering it unfit for further cleanliness testing. This is indicated in the results (Tables 1-3) using the symbol N/A in one column or the other.

However, the total low volatility residue (LVR) analysis and the residual chloride analysis (Cl^-) are not mutually exclusive, and both examinations can be performed on the same sample. They are not mutually exclusive because first an extract is made using D.I. water to remove the very soluble anions present (Cl^-, F^-, Br^-), and then an extract is made using the Freon TF/IPA to remove the rosin residue which is insoluble in water.

The results for the new centrifugal cleaning system using the aqueous chemistry are reported in Tables 1-3 below. Table 4 gives ionic contamination levels using the older SA cleaning system.

The outgassing test method per ASTM E595 covers a screening technique to determine the volatile content of materials when exposed to a vacuum environment. Two parameters must be measured: Total mass loss (TML) and collected volatile condensable material (CVCM). In addition, since polyimide printed wiring board material can absorb moisture, an additional parameter was determined, namely, the amount of water vapor regained (WVR). The results are reported in Table 5 below; TML, CVCM and TML - WVR are reported.

Acceptable Cleanliness Levels

Per JPL D-8208, *Spacecraft Design and Fabrication Requirements for Electronic Packaging and Cabling*, the ionic contamination level as determined by the Ionograph must not exceed 10 micrograms per square inch (10 $\mu g/in^2$). If it does, the entire lot of PWBs must be recleaned and one PWB per lot retested until this ionic cleanliness level is achieved.

No acceptable standard has been agreed upon for the amount of residual rosin; however, a limit of no more than 150 micrograms per square inch (150 $\mu g/in^2$) seems appropriate.

In the case of ionic profiling using ion chromatography (IC), no acceptable standards has been agreed upon for the amount of individual ionic species, but one would expect that the sum of the various ionic species would be less than the limit obtained from ionic contamination testing, that is, 10 micrograms per square inch.

Per the outgassing determination per ASTM E595, the acceptable level for the TML must be no more than 1.00%, and the CVCM must be no more than 0.10%. If the WVR is determined , then TML – WRV is also reported.

Test Runs

Three test runs made with the new centrifugal cleaning machine using the aqueous cleaning solution are presented in Tables 1-3. As a comparison, a test run using the older SA cleaning system is presented in Table 4.

Test Run #1 – New Cleaning System

Centrifugal cleaning system with the aqueous cleaning solution was used. The aqueous cleaning system consisted of 20% by volume of the long chain alcohol solution, 1% by volume of the corrosion inhibitor, and 0.1% by volume of the defoamer. The wash solution temperature was 50°C; the rinse solution temperature was 50°C; the dry air temperature was 200°C; the wash cycle rotational speed = 150 RPM. NOTE: The four different batches signify that the run was repeated at four different times. Ionic contamination testing using the Ionograph was done as a cleanliness check on some of the test PWAs. In addition, total low volatility residue (LVR) analysis and the residual chloride analysis (Cl^-) were performed on other PWAs. The results are found in Table 1.

Wash time = 5.0 min.; rinse time = 2.5 min.; dry time = 2.5 min.

Table 1 Cleanliness Data of Test Run #1

Test PWA Serial No.	Batch No.	Ionograph Results µg/in^2	Low Volatility Residue µg/in^2	Remarks
16	1	0.40	N/A	
14	1	0.23	N/A	Batch 1 mean ionic contamination level = 0.32
18	2	0.00	N/A	
19	2	0.17	N/A	Batch 2 mean ionic contamination level = 0.09
8	3	0.60	N/A	
24	3	0.40	N/A	
9	3	0.04	N/A	
25	3	0.02	N/A	Batch 3 mean ionic contamination level = 0.27
26	4	N/A	3.2	Cl^- residue < 0.001
10	4	N/A	6.5	Cl^- residue < 0.001
Parts removed	4	N/A	0.5	Cl^- residue < 0.005
7	Uncleaned PWB	152.2	N/A	

Test Run #2 – New Cleaning System

Centrifugal cleaning system with the aqueous cleaning solution was used. The aqueous cleaning system consisted of 20% by volume of the long chain alcohol solution, 1% by volume of the corrosion inhibitor, and 0.1% by volume of the defoamer. The wash solution temperature was 50°C; the rinse solution temperature was 50°C; the dry air temperature was 200°C; the wash cycle rotational speed = 150 RPM. The two different batches signify that the run was repeated at two different times. Ionic contamination testing using the Ionograph was done as a cleanliness check on some of the test PWAs. In addition, total low volatility residue (LVR) analysis was performed on several PWAs. The results are found in Table 2.

Wash time = 3.0 min.; rinse time = 2.0 min.; dry time = 2.0 min.

Table 2 Cleanliness Data of Test Run #2

Test PWA Serial No.	Batch No.	Ionograph Results µg/in^2	Low Volatility Residue µg/in^2	Remarks
15	1	1.35	N/A	
17	1	1.47	N/A	Batch 1 mean ionic contamination level = 1.41
27	1	N/A	6.5	
28	2	0.36	N/A	Batch 2 mean ionic contamination level = 0.36
29	2	N/A	0.5	Parts were removed from PWB first

Test Run #3 – New Cleaning System

Centrifugal cleaning system with the aqueous cleaning solution was used. The aqueous cleaning system consisted of 20% by volume of the long chain alcohol solution, 1% by volume of the corrosion inhibitor, and 0.1% by volume of the defoamer. The wash solution temperature was 50°C; the rinse solution temperature was 50°C; the dry air temperature was 200°C; the wash cycle rotational speed = 150 RPM. Ionic contamination testing using the Ionograph was done as a cleanliness check on some of the test PWAs. Also, total low volatility residue (LVR) analysis, residual chloride analysis (Cl^-), and in addition, residual fluoride analysis (F^-) and bromide analysis (Br^-) were performed on other PWAs. In Table 3 the two aluminum plates were cleaned along with the PWAs, but they were not exposed to the solder paste. The results are found in Table 3.

Wash time = 6.0 min.; rinse time = 6.0 min.; dry time = 3.0 min.

Table 3 Cleanliness Data of Test Run #3

Test PWA Serial No.	Batch No.	Ionograph Results µg/in^2	Low Volatility Residue µg/in^2	Remarks
4	1	N/A	8.4	Rework was simulated and some flux applied to this PWB
5	1	N/A	1.9	
11	1	N/A	1.6	
12	1	N/A	2.3	
102	2	N/A	5.8	Cl^- residue < 0.000; F^- residue < 0.000; Br^- residue < 0.000
103	2	N/A	0.7	Cl^- residue < 0.000; F^- residue < 0.000; Br^- residue < 0.000
104	2	N/A	0.7	Cl^- residue < 0.000; F^- residue < 0.000; Br^- residue < 0.000
108	2	N/A	1.4	Cl^- residue < 0.000; F^- residue < 0.000; Br^- residue < 0.000
124	2	N/A	2.6	Cl^- residue < 0.001; F^- residue < 0.000; Br^- residue < 0.000
Al plate #1	2	N/A	0.7	Cl^- residue < 0.003; F^- residue < 0.002; Br^- residue < 0.062
Al plate #2	2	N/A	0.4	Cl^- residue < 0.003; F^- residue < 0.002; Br^- residue < 0.062
Solvent (Control)	2	N/A	0.0	Cl^- residue < 0.001; F^- residue < 0.002; Br^- residue < 0.000

Table 3 Cleanliness Data of Test Run #3 (cont.)				
105	3	3.19	N/A	
106	3	1.12	N/A	
107	3	1.60	N/A	Batch 3 mean ionic contamination level = 1.97
122	Uncleaned PWB	N/A	2462	Bare PWB with solder paste printed on it.
123	Uncleaned PWB	N/A	33	Bare PWB with solder paste printed on it and then reflowed.

Test Run #4 – Old Cleaning System

The two-stage batch semi-aqueous (SA) cleaning system was used. The first stage consists in placing the PWAs vertically in a suitable conventional rack followed by cleaning using a terpene-based SA material and water. The PWAs were then transferred to the second machine and rinsed using a suitable saponifier, isopropyl alcohol (IPA), and D.I. water. The conventional wash/rinse/dry cycle was used. The results are found in Table 4.

Wash time = 5.0 min.(with saponifier); rinse time = 10.0 min. (D.I. H_2O); 5.0 min. (D.I. H_2O/IPA mixture); dry time = 5.0 min.

Table 4 Cleanliness Data of Test Run #4

Test PWA Serial No.	Batch No.	Ionograph Results µg/in^2	Low Volatility Residue µg/in^2	Remarks
21	1	8.05	Not performed	
22	1	3.32	Not performed	
23	1	2.76	Not performed	Batch 1 mean ionic contami- nation level = 4.71

Outgassing Data

The two samples on which the ASTM E595 outgassing test was performed were part of Test Run #3.

Table 5 Outgassing Data of Test Run #3

Test PWA Serial No.	Batch No.	TML %	CVCM %	TML - WVR %	Remarks
121	2	0.260	0.002	0.187	This sample was a printed wiring board only.
101	2	0.253	0.000	0.184	This sample was a printed wiring board assembly.

Summary of Results

The results are summarized as follows:

- PWAs cleaned with 5.0 minutes wash and 2.5 minutes rinse had average ionic cleanliness level of 0.27 micrograms per square inch, far below the JPL maximum acceptable ionic cleanliness level of 10 micrograms per square inch. This result is much lower than that obtained by the older cleaner. See Table 5.
- PWAs cleaned with 5.0 minutes wash and 2.5 minutes rinse had average LVR cleanliness level of 4.84 micrograms per square inch. Although no standard exists for LVR, it is less than 6.45 micrograms per square inch, which is the lowest level of the flight hardware determination standard MIL-STD-1246C Level A.
- PWAs cleaned with 3.0 minutes wash and 2.0 minutes rinse had average cleanliness level of 0.93 micrograms per square inch, far below the JPL maximum acceptable ionic cleanliness level of 10 micrograms per square inch. This result is much lower than that obtained by the older cleaning system. See Table 4. The results, however, are not optimal.
- The anion profile analysis performed with ion chromatography showed exceedingly low levels of anion species, thus indicating very low levels of remaining contamination.
- The outgassing data for the boards cleaned using the new centrifugal cleaning system/aqueous chemistry indicates that the TML is much less than 1.00% and the CVCM is much less than 0.10%.
- The optimal cleaning cycle suggested by the data is:
  - Wash solution temperature 50°C
  - Rinse solution temperature 50°C
  - Dry air temperature 200°C
  - Wash cycle rotational speed = 150 RPM
  - Wash time = 5 min.
  - Rinse time = 2.5 min.
  - Dry time = 2.5 min.

Conclusion

The centrifugal cleaner using the new aqueous cleaning solution based on long-chain alcohols shows a marked improvement in cleanliness of PWAs over the previous two-stage batch semi-aqueous (SA) cleaning system using a terpene-based SA material and water in machine #1 for cleaning and saponifier, isopropyl alcohol (IPA), and D.I. water in machine #2 for rinsing. The centrifugal cleaner using the new aqueous cleaning solution not only cleans at a higher degree of cleanliness level compared to the older SA cleaning system, but also it is cost effective to use. The total cycle time is about 50% less than the older SA cleaning system. Also, it uses single chemical (the long-chain alcohol/aqueous solution) with very small amount of additives compared to three chemicals used by the older SA cleaning system. The use of hazardous isopropyl alcohol is also eliminated.

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Figure 1 View of the centrifugal cleaning system

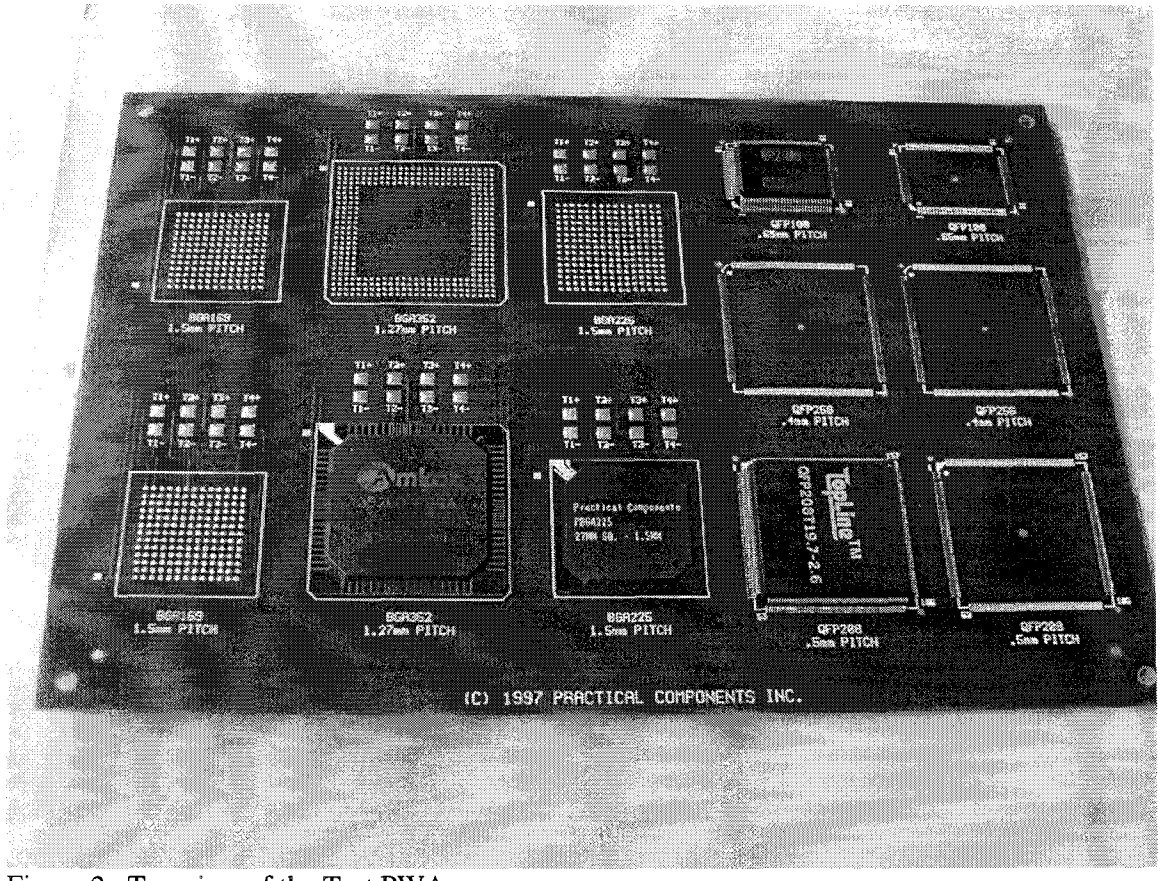

Figure 2 Top view of the Test PWA

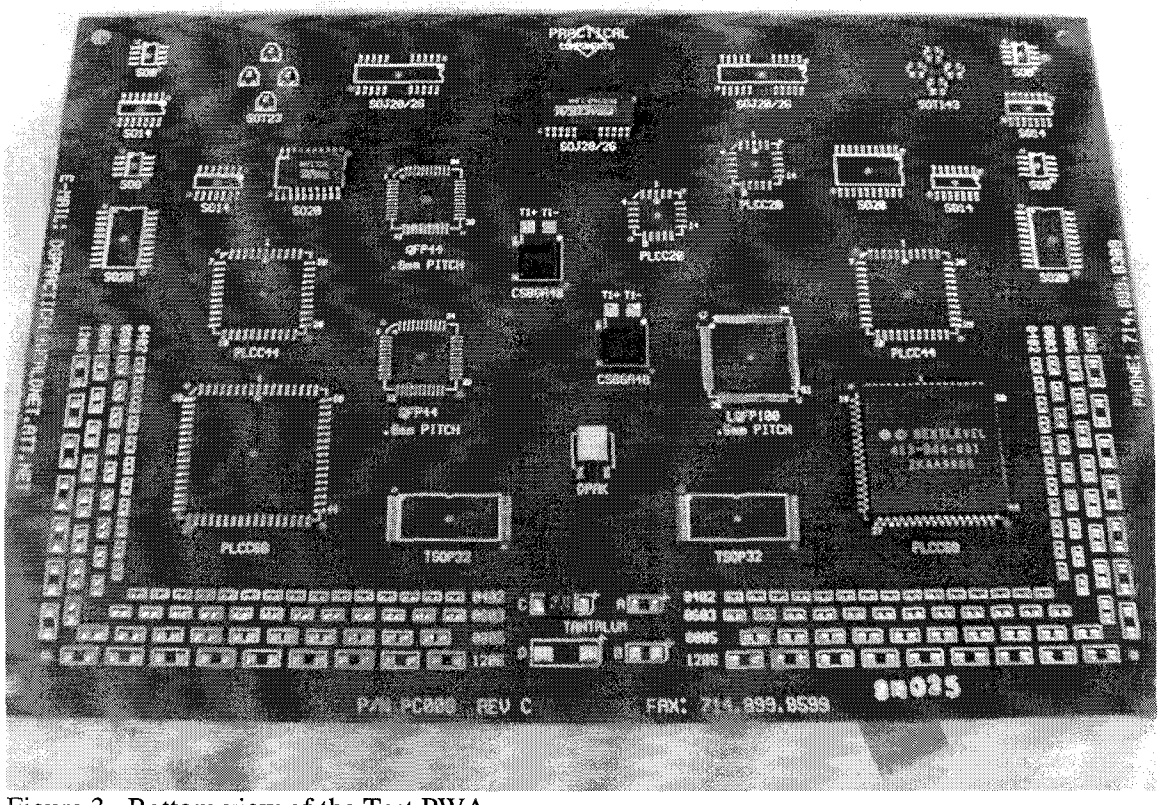

Figure 3 Bottom view of the Test PWA